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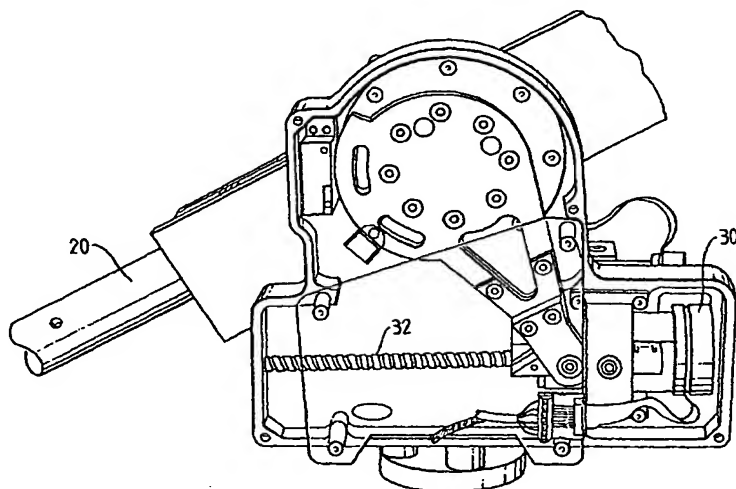
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[Continued on next page]

(54) Title: **ROBOT HEAD COMPRISING SPINDLE DRIVE**



(57) Abstract: A robot head, for example for use in surgery, provides a back-drivable system allowing a surgeon to closely control the position of a cutter or other tool. The cutter is mounted at the end of a telescopic arm (20) which can be rotated about two independent perpendicular axes. Rotation about each axis is controlled by a separate motor (30') which turns a lead screw (32). A bearing (34) travels along the lead screw and changes the angle of an offset crank (36) to cause the required rotation about the axis. The current rotational position about each axis is determined by a sensor at the output. A second sensor independently determines the position of the corresponding motor (30) and the two measured positions are compared. If they differ, the power to the cutter is immediately switched off.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

ROBOT HEAD COMPRISING SPINDLE DRIVE

The present invention relates to robot heads and particularly, although not exclusively, to a head for a surgical robot.

5

In one type of robotically-assisted surgical procedure, a cutting implement (for example to cut bone) is mounted on an adjustable robot head which is itself held in position by a static gross-positioning device. The robot head has a manually-graspable handle which allows the surgeon to move the cutter.

10 Typically, the cutter may be mounted at the end of a telescopic arm, and by applying force to the handle the surgeon may cause the arm to extend and/or to rotate about mutually-perpendicular pitch and yaw axes. Motors within the head respond to forces applied to the handle to ensure that the cutter moves smoothly to the position the surgeon requires. The head may include
15 constraint mechanisms, implemented either in hardware or in software, which prevent the surgeon from moving the cutter into regions which have previously been defined as unsafe. Force feedback mechanisms may also be provided so that the surgeon receives tactile force feedback through the handle.

20 Of particular importance in surgical applications – although it may be of importance in other applications as well – is the precision with which the cutter can be positioned by the surgeon. Current systems are somewhat limited in this respect, because of relatively high friction in the mechanical components, along with a certain amount of “play” or backlash. A further requirement of
25 course is safety, and concerns have been expressed as to the potentially serious injuries that could be caused to a patient in the event of a mechanical failure of a traditional robot head, or a failure in the control system or its software.

It is an object of the present invention at least to alleviate these perceived difficulties.

According to a first aspect of the present invention there is provided a back-
5 drivable robot head including:

- (a) a manually-graspable driving member;
- (b) a force sensor for sensing forces applied to the driving member by a
user
- (c) an arm for carrying a tool the position of which is to be controlled;
10 and
- (d) a first rotation control mechanism for rotating the arm about a first
axis in response to the sensed forces;

characterised in that the first rotation control mechanism comprises a first
rotational motor coupled to a first lead screw; and a bearing which moves
15 longitudinally of the first lead screw as it rotates, the bearing being pivotally
coupled to an offset crank of or secured to the arm.

According to a second aspect of the present invention there is provided a back-
drivable robot head including:

- (a) a manually-graspable driving member;
- (b) a force sensor for sensing forces applied to the driving member by a
user
- (c) an arm for carrying a tool the position of which is to be controlled;
and
- 25 (d) a first rotation control mechanism for rotating the arm about a first
axis in response to the sensed forces;

characterised in that the first rotation control mechanism comprises a first
rotational motor, an output of which is converted first to longitudinal motion
and then back to rotational motion of the arm.

According to a third aspect of the present invention there is provided a back-drivable robot head including:

- (a) a manually-graspable driving member;
- (b) a force sensor for sensing forces applied to the driving member by a user
- (c) an arm for carrying a tool the position of which is to be controlled; and
- (d) a first rotation control mechanism for rotating the arm about a first axis in response to the sensed forces;

characterised in that the first rotation control mechanism comprises a first rotational motor, an output of which is converted first to longitudinal motion and then back to rotational motion of the arm; the head further including a first input encoder for measuring rotation of the first motor, a first output encoder for measuring the angular position of the arm about the first axis, and in which the measurement from the first output position encoder is compared with an expected arm position based on the measurement from the first input position encoder, an alarm being raised if the expected position is inconsistent with the actual position.

The invention may be carried into practice in a number of ways, and one specific embodiment will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a schematic view of a preferred surgical robot head, with the covers removed;

Figure 2 shows the rear mounting, for mounting the head onto a gross positioning device;

Figure 3 is a view from below, showing rotational control of the telescopic arm about a vertical axis;

Figure 4 shows the telescopic arm at one extreme end of its range of rotation;

Figure 5 shows the arm at the other extreme end of its range;

Figure 6 shows the pivotal connection between the offset crank and the lead screw;

Figure 7 shows the mounting of the motor that drives the lead screw;

5 Figure 8 shows the primary sensor which determines rotational position;

Figure 9 shows the telescopic arm at the two extreme limits of its range;

Figure 10 shows the tracks on which the telescopic arm moves.

10 Figure 1 shows a surgical robot head in accordance with a preferred embodiment of the invention. The head consists of a generally L-shaped frame 10 having an upper portion 12 and a lower portion 14. The upper portion 12 has a rotatable mounting 16, best shown in Figure 2, having a rear mounting plate 17 which allows the head to be bolted to a static gross positioning device (not shown). Once so mounted, the whole of the robot head
15 can then rotate about a horizontal pitch axis, as shown by the arrows 18.

Mounted to the lower portion 14 of the frame is a telescopic arm 20, capable of extending and retracting by means of a motor 28, as shown by the arrows 22. The arm is mounted for rotation about a vertical yaw axis, as shown by the
20 arrows 24. The horizontal pitch axis and the vertical yaw axis intersect on the longitudinal axis of the arm 20.

In use, a cutter (not shown) is inserted into a bore 26 at one end of the arm, and is locked into place by means of a locking handle 27.

25 The surgeon operating the device grasps a handle 30, and manually guides the cutter through the bone as required. Sensors within the handle 30 or between the handle and the body detect the forces that are being applied, and adjust the pitch, yaw and in/out motions accordingly, as will be described in more detail below. It will be understood of course that in the operating theatre most of the

mechanical parts displayed in Figure 1 will be hidden behind smooth external covers; these have been omitted from Figure 1 to expose the workings of the head.

5 Figure 3 is a view from below, showing the mechanism for controlling rotational movement of the arm 20 about the vertical yaw axis. Rotation of a lead screw 32 by means of a pancake or other motor 30' causes a ball screw or bearing 34 to move up and down the lead screw. The ball screw 34 is connected to an arm or crank 36 which is itself connected to the telescopic arm
10 20. Accordingly, the yaw position of the arm 20 is controlled by the linear position of the ball screw 34 on the lead screw 32.

The crank arm 36 connects to the lead screw 32 by means of a pivoting linkage, to allow for the different angles of the crank arm as the ball screw 34 moves
15 along. Movement also causes the lead screw 32 to rotate slightly about a pivot bearing 40 adjacent the motor 30'.

Figures 4 and 5 show, respectively, the arm 20 at each end of its range of movement. As may be seen, in both of these extreme positions, the lead screw
20 32 is substantially horizontal in the drawing; compare this with Figure 3, in which the lead screw 32 has been pushed downwards slightly due to the length of the crank 36.

Figure 6 is a close-up view showing in more detail the pivotal coupling
25 between the crank arm 36 and the lead screw 32. Figure 7 is a further close-up showing the pivotal coupling of the motor 30' and the crank arm 32 with respect to the lower part 14 of the frame.

As is best seen in Figure 6, the lead screw 32 is formed with a high lead angle: this allows for low gear ratios to be used, as well as allowing the system to be back drivable (in other words, the surgeon can simply pull the arm 20 around by grasping the handle 30 shown in Figure 1). With the arrangement
5 described, no gear box is required, and the motor 30' (Figure 3) is simply attached directly to the end of the lead screw 32.

Turning back now to Figure 3, it will be seen that surrounding the vertical yaw axis is a cylindrical structure 37. This is used in order to determine the exact
10 rotational position of the arm 20, in conjunction with an encoder generally indicated at 38. As is best shown in Figure 8, the cylindrical structure 37 defines a circumferential cam surface 40 onto which is secured a thin reflective strip 42. A sensor 44 picks up patterns (not shown) on the strip, from which the angular position of the arm 20 may be accurately determined. In this
15 embodiment, a stop 46 defines a nominal zero position, with the actual position at any time simply being determined by counting the number of pulses the sensor 44 has detected as the arm moves away from the zero position. The use of a circumferential strip 42 as described substantially eliminates errors due to backlash.

20

In order to protect against mechanical or other fault, an additional safety sensor (not shown) is built into the motor 30'. Position signals from the motor's sensor and from the main sensor 44 are compared and, if there is any discrepancy, an alarm is raised and the power to the cutter is switched off
25 immediately. Because of the changing angles of the crank arm 36, there is not a linear relationship between the pulses detected by the motor sensor and those detected by the main sensor 44. Accordingly, it is convenient for the comparison to be carried out in software. Suitable software will not be described here, as it is well within the capabilities of a skilled person in the

field to construct a function or a mapping defining the non-linear relationship, and then setting up a comparison with appropriate trigger points for switching off the power.

5 Turning back to Figure 1, it will be seen that the mechanism for controlling rotation of the head about the horizontal pitch axis, on the mount 16, is virtually identical to the mechanism already described for rotation about the vertical yaw axis. The mechanisms within the upper part 12 of the frame 10, and surrounding the mount 16, will not therefore be described separately.

10

Figure 9 shows the arm 20 in its retracted position 50 and in an extended position 52. Extension is effected by means of the motor 28 (Figure 1) which turns a lead screw 54. Unlike the motors for the yaw/pitch actions, this motor is fixed in position. As the motor rotates and the screw turns, a barrel portion 15 56 of the arm, mounted to a carriage, is moved along the guide tracks 58.

Between the rails 58 is a positioning strip 60. The position of the carriage with respect to this strip is sensed by means of a position sensor (not visible in the drawings) positioned beneath the barrel 56. Just visible at the left hand edge 20 of Figure 10 is a carriage stop which acts as a zero-point indicator. The exact location of the carriage along the rails 50 is determined by the number of pulses received by the sensor from corresponding markings on the strip as the carriage moves away from the zero point.

25 For additional security, a secondary sensor (not shown) is provided in association with the motor 28. A hardware or software comparison is made between the measured position of the barrel 56 as determined by the main sensor, and the position as determined by the secondary sensor. If the sensors

do not agree, an alarm is raised and power to the cutter is immediately switched off.

5 The manually-graspable knob 30, best seen in Figure 1, has a force sensor (not shown) mounted within it, along with associated wiring and electronics. The outer part of the knob is connected to the sensor which is itself connected to the arm 20. Hence, any force the surgeon applies to the knob 30, in any direction, will automatically be sensed by the sensor. The sensor generates control signals based upon the sensed forces which are used, along with details of the
10 current head position and cutter constraints, to control the pitch and yaw motors 30', along with the arm extension motor 28. The motors are controlled so that the surgeon feels an increasing resistance as he pushes towards a constraint boundary, and decreasing resistance as he moves away. In an unconstrained region, the motors are controlled to give an equal low resistance
15 to movement in any direction. For the present purpose, an unconstrained region means either:

- (a) when the constraints are switched off (e.g. during registration), or
- (b) far away from any boundary, inside the constraint region.

20 When the surgeon needs to cut bone, an appropriate cutter is pushed into the bore 26, and locked in place by the locking handle 27 (Figure 1). Alternatively, other surgical or medical instruments may be placed within the bore 26, depending upon the application.

25 The robot head described may also be used in non-surgical applications.

CLAIMS:

1. A back-drivable robot head including:
 - (a) a manually-graspable driving member;
 - 5 (b) a force sensor for sensing forces applied to the driving member by a user;
 - (c) an arm for carrying a tool the position of which is to be controlled; and
 - (d) a first rotation control mechanism for rotating the arm about a
10 first axis in response to the sensed forces;characterised in that the first rotation control mechanism comprises a first rotational motor (30') coupled to a first lead screw (32); and a bearing which moves longitudinally of the first lead screw as it rotates, the bearing being pivotally coupled to an offset crank (34) of or secured to the arm.
15
2. A robot head as claimed in claim 1 in which the first motor and the first lead screw are mounted for pivotal motion with respect to a frame of the head.
3. A robot head as claimed in claim 1 or claim 2 in which the first motor is
20 directly secured to the first lead screw, without any intervening gears.
4. A robot head as claimed in any one of the preceding claims in which the first lead screw has a high lead angle.
- 25 5. A robot head as claimed in any one of the preceding claims including a first output position encoder for measuring the angular position of the arm about the first axis.

6. A robot head as claimed in any one of the preceding claims including a first input position encoder for measuring rotation of the first motor.
7. A robot head as claimed in claim 5 and claim 6 in which the measurement from the first output position encoder is compared with an expected arm position based on the measurement from the first input position encoder, and an alarm is raised if the expected position is inconsistent with the actual position.
8. A robot head as claimed in any one of the preceding claims including a second rotation control mechanism for rotating the arm about a second axis, the said mechanism comprising a second rotational motor (30') coupled to a second lead screw (32); and a bearing which moves longitudinally of the second lead screw as it rotates, the bearing being pivotably coupled to an offset crank (34) of or secured to the arm.
9. A robot head as claimed in claim 8 in which the second motor and the second lead screw are mounted for pivotal motion with respect to a frame of the head.
10. A robot head as claimed in claim 8 or claim 9 in which the second motor is directly secured to the second lead screw, without any intervening gears.
11. A robot head as claimed in any one of claims 8 to 10 in which the second lead screw has a high lead angle.
12. A robot head as claimed in any one of claims 8 to 11 including a second output position encoder for measuring the angular position of the arm about the second axis.

13. A robot head as claimed in any one of claims 8 to 12 including a second input position encoder for measuring rotation of the second motor.

5 14. A robot head as claimed in claim 12 and claim 13 in which the measurement from the second output position encoder is compared with an expected arm position based on the measurement from the second input position encoder, and an alarm is raised if the expected position is inconsistent with the actual position.

10

15. A robot head as claimed in any one of claims 8 to 14 in which the first axis is perpendicular to the second.

15

16. A robot head as claimed in any one of the preceding claims in which the arm is extendible along a third axis.

17. A robot head as claimed in claim 15 and claim 16 in which the first, second and third axes intersect at a point.

20

18. A robot head as claimed in claim 16 in which the arm is extendible on a third lead screw which is rotated by a third rotational motor.

19. A robot head as claimed in any one of claims 16 to 18 including a third output position encoder for measuring the extension position of the arm.

25

20. A robot head as claimed in claim 18 including a third input position encoder for measuring rotation of the third motor.

21. A robot head as claimed in claim 19 and claim 20 in which the measurement from the third output position encoder is compared with an expected arm extension position based on the measurement from the third input encoder, and an alarm is raised if the expected position is inconsistent with the actual position.

22. A back-drivable robot head including:

- (a) a manually-graspable driving member;
- (b) a force sensor for sensing forces applied to the driving member by a user;
- (c) an arm for carrying a tool the position of which is to be controlled; and
- (d) a first rotation control mechanism for rotating the arm about a first axis in response to the sensed forces;

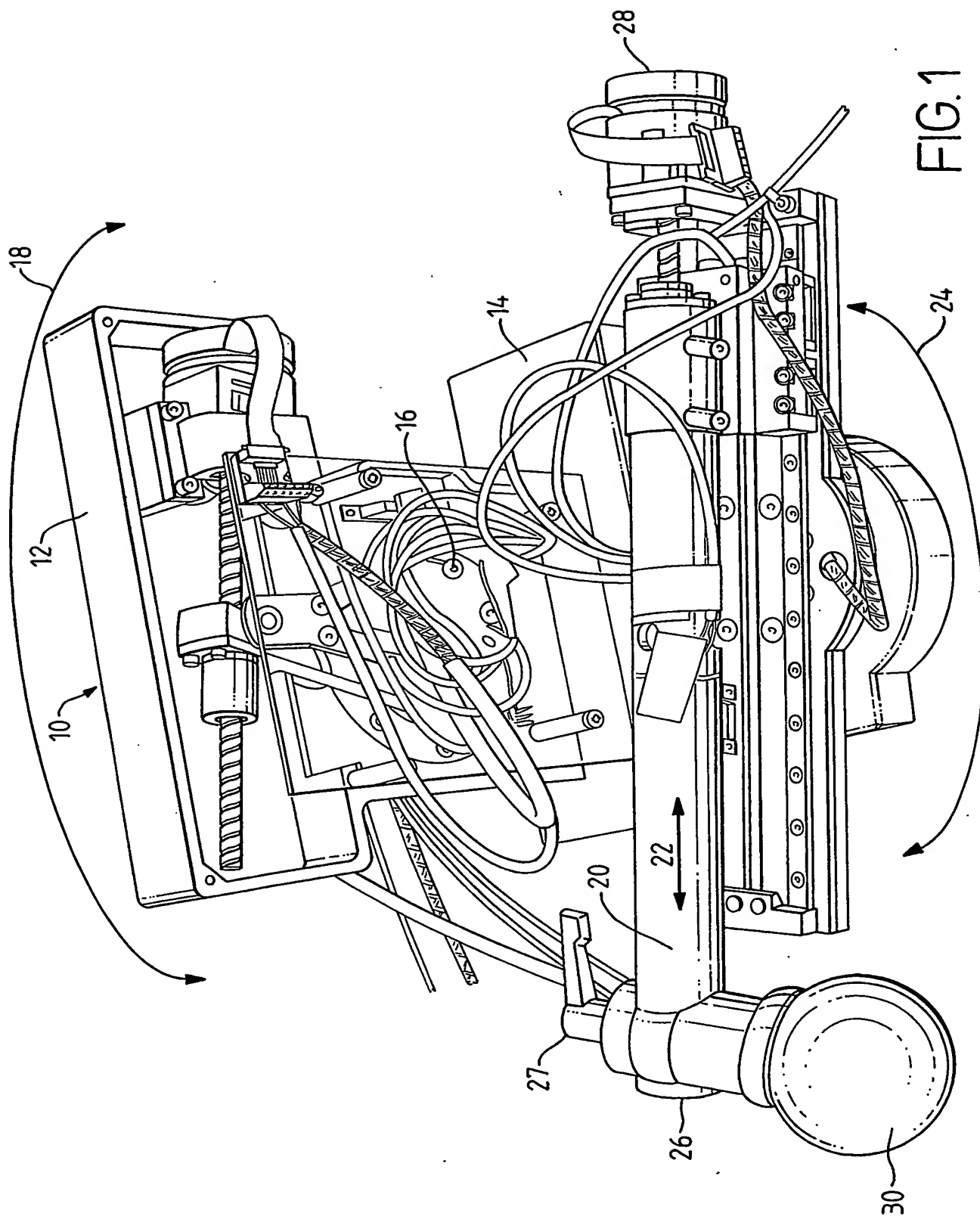
characterised in that the first rotation control mechanism comprises a first rotational motor (30'), an output of which is converted first to longitudinal motion and then back to rotational motion of the arm.

23. A back-drivable robot head including:

- (a) a manually-graspable driving member;
- (b) a force sensor for sensing forces applied to the driving member by a user;
- (c) an arm for carrying a tool the position of which is to be controlled; and
- (d) a first rotation control mechanism for rotating the arm about a first axis in response to the sensed forces;

characterised in that the first rotation control mechanism comprises a first rotational motor (30'), an output of which is converted first to longitudinal motion and then back to rotational motion of the arm; the head further

including a first input encoder for measuring rotation of the first motor (30'), a first output encoder for measuring the angular position of the arm about the first axis, and in which the measurement from the first output position encoder is compared with an expected arm position based on the measurement from the first input position encoder, an alarm being raised if the expected position is inconsistent with the actual position.



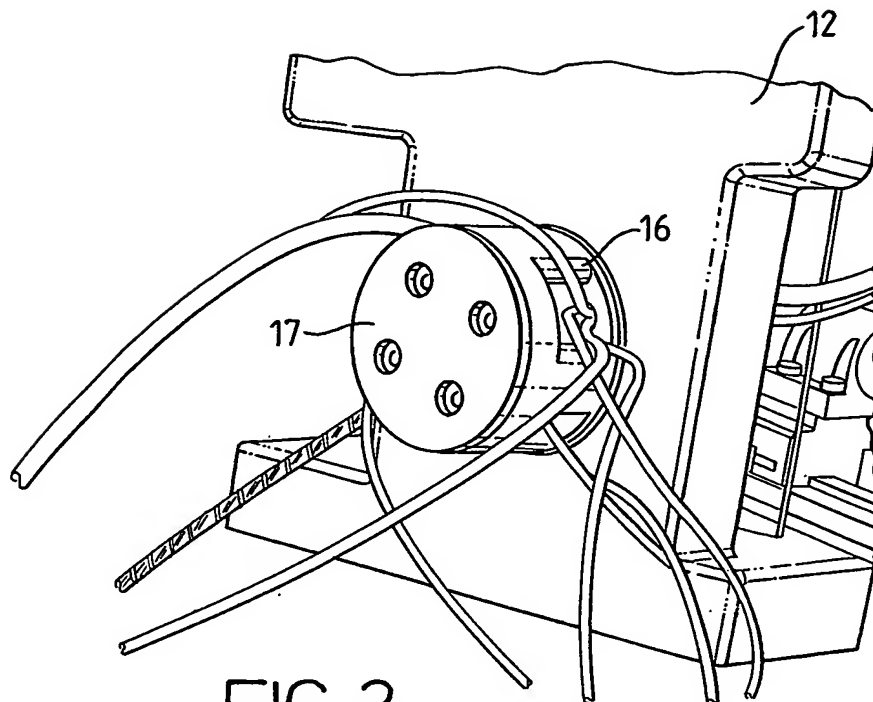


FIG. 2

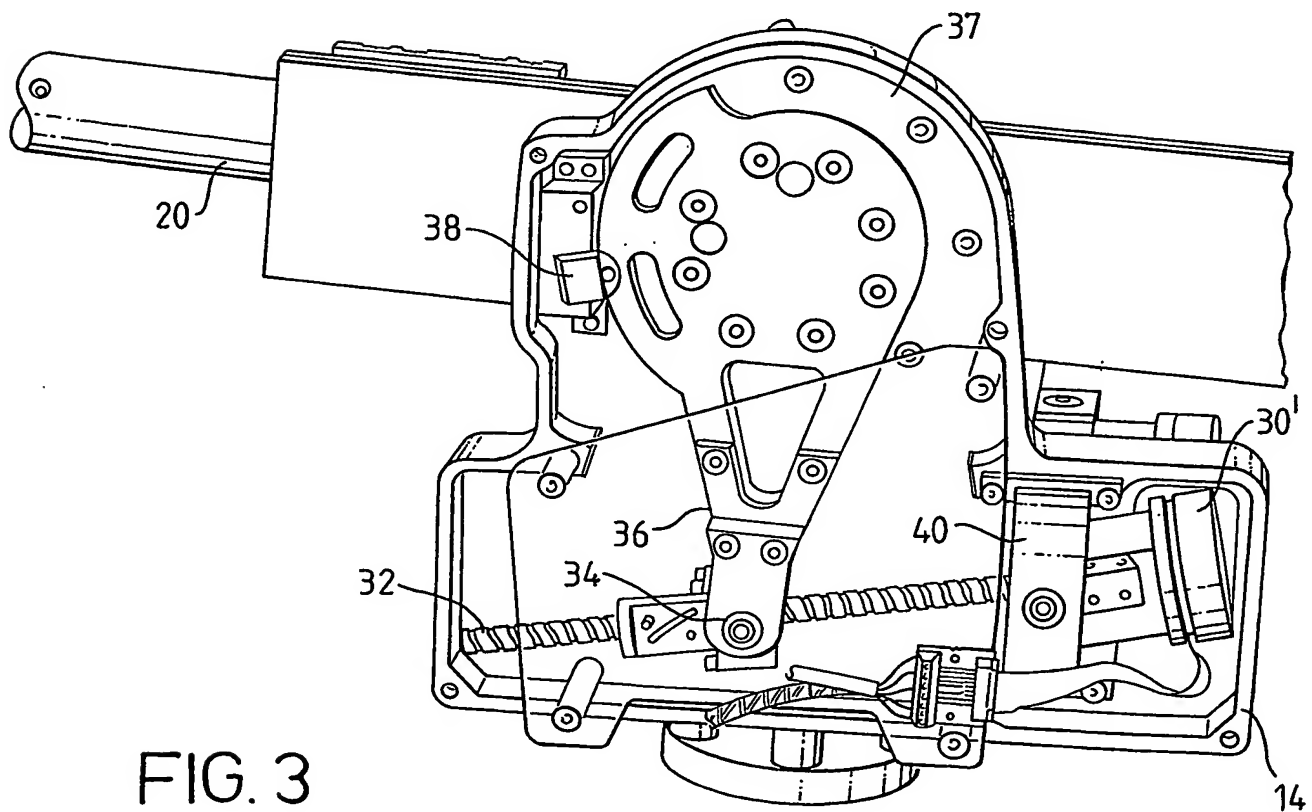
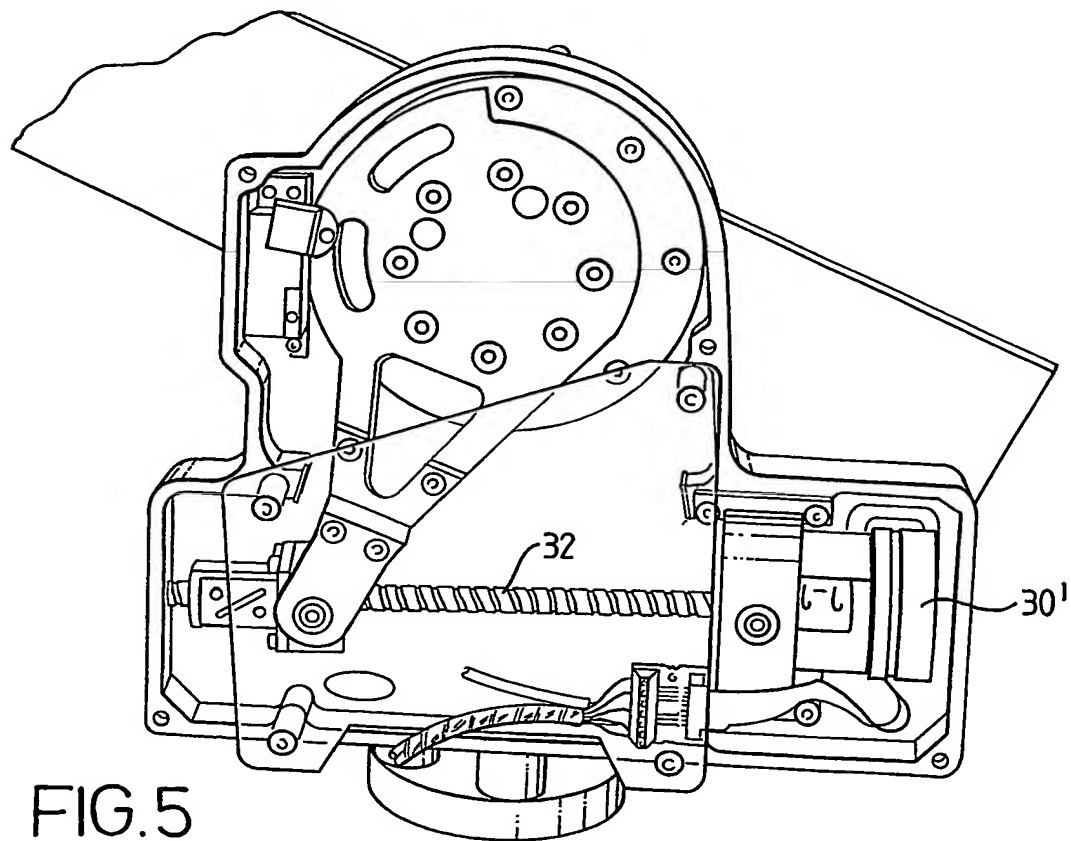
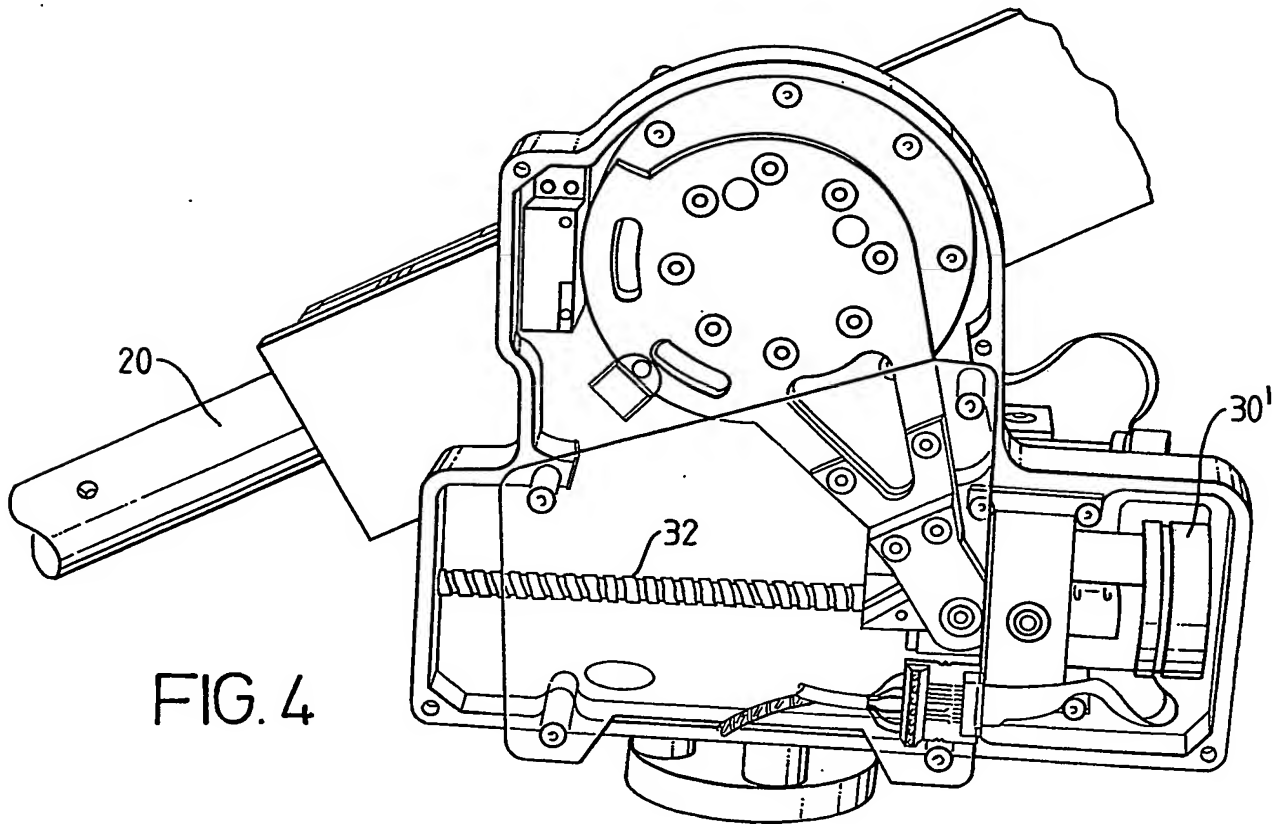


FIG. 3



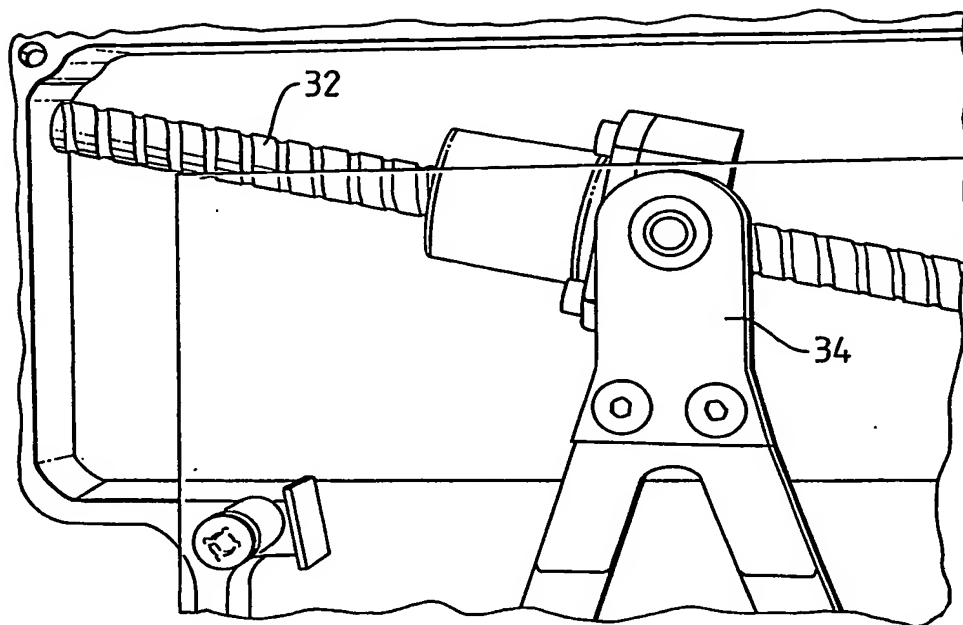


FIG. 6

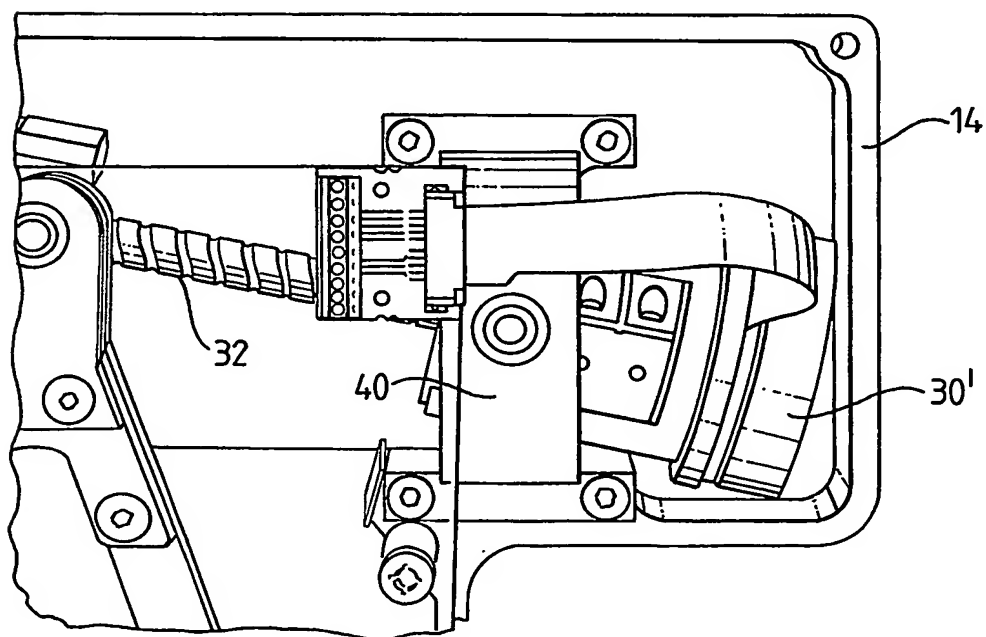


FIG. 7

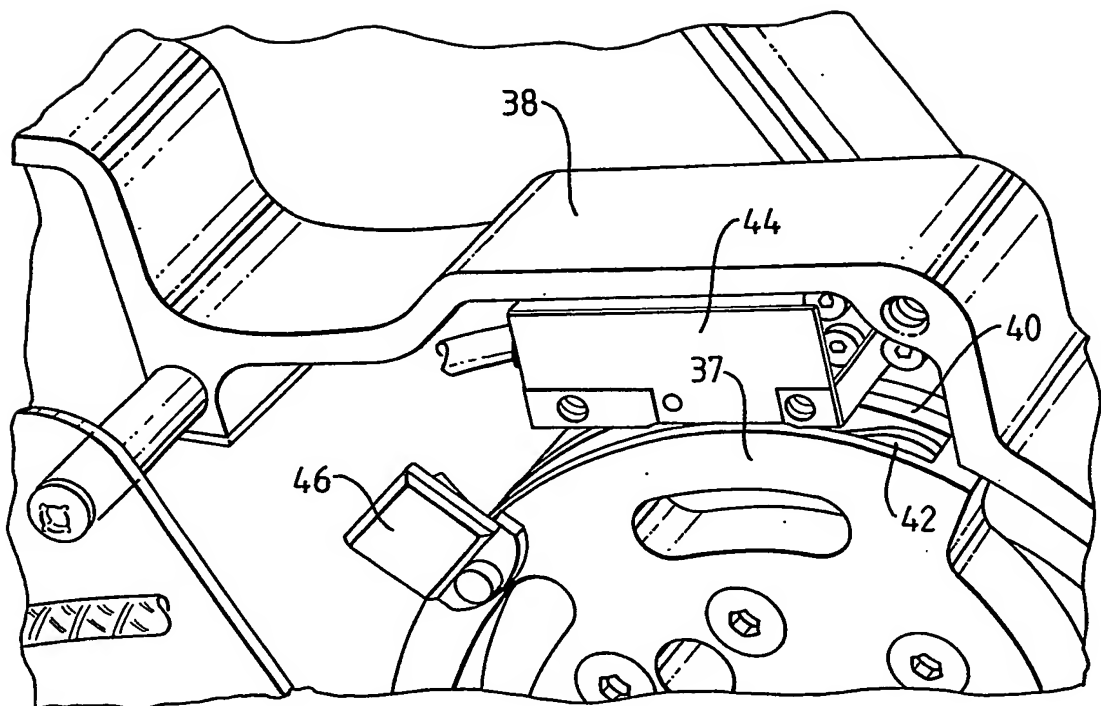


FIG. 8

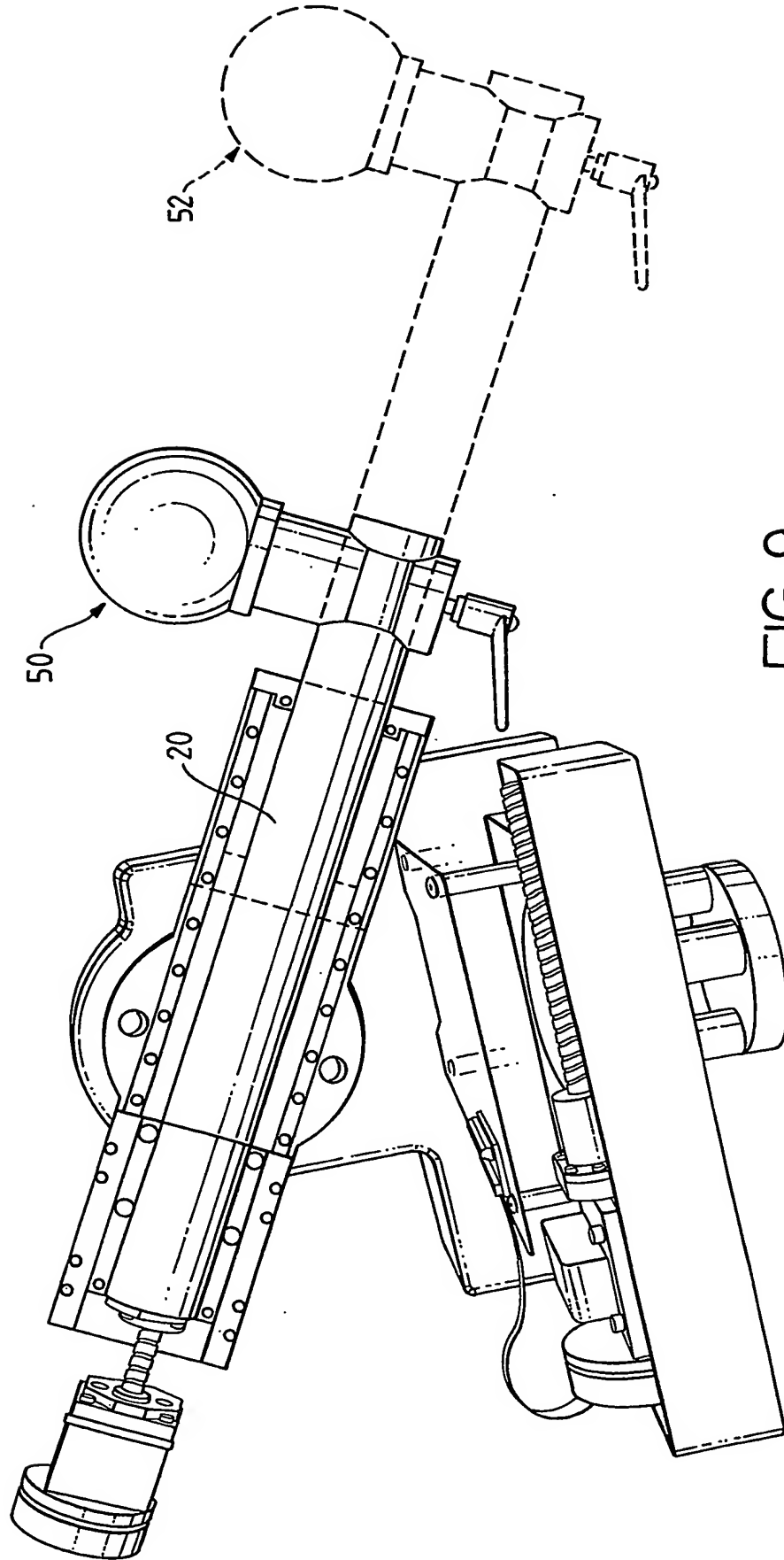


FIG. 9

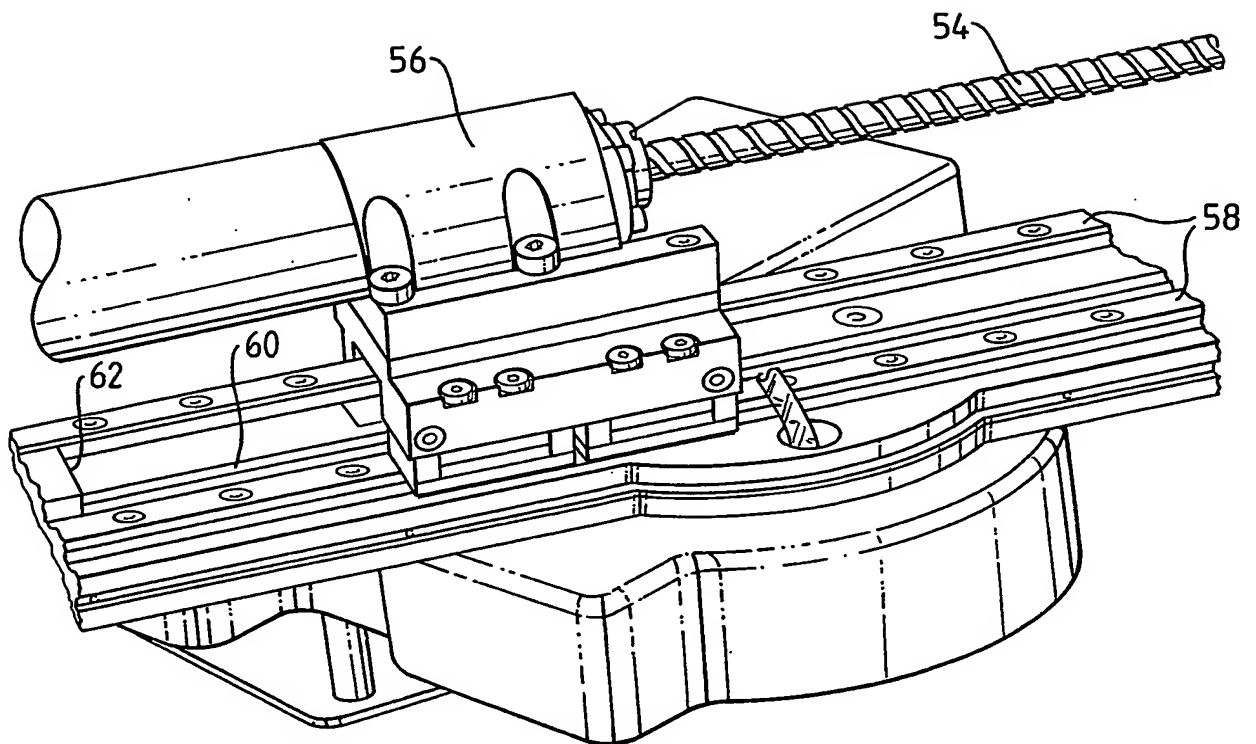


FIG. 10

INTERNATIONAL SEARCH REPORT

PCT/GB 03/03354

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 A61B19/00 B25J18/00 B25J9/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 A61B B25J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 02 060653 A (ACROBOT COMPANY LTD ;DAVIES BRIAN LAWRENCE (GB); JAKOPEC MATJAZ (G) 8 August 2002 (2002-08-08) the whole document ----	1-21
Y	US 4 430 037 A (BISIACH LUCIANO) 7 February 1984 (1984-02-07) column 2, line 53 -column 4, line 14 ----	1-21
A	US 2002/120254 A1 (FREUND JOHN G ET AL) 29 August 2002 (2002-08-29) the whole document -----	1-21

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents :

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.
- * & * document member of the same patent family

Date of the actual completion of the international search

23 January 2004

Date of mailing of the international search report

06/02/2004

Name and mailing address of the ISA

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Authorized officer

Held, G

INTERNATIONAL SEARCH REPORT

PCT/GB 03/03354

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 22, 23
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
see FURTHER INFORMATION sheet PCT/ISA/210

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this International application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

Continuation of Box I.2

Claims Nos.: 22,23

In view of the large number and also the wording of the claims presently on file, which render it difficult, if not impossible, to determine the matter for which protection is sought, the present application fails to comply with the clarity and conciseness requirements of Article 6 PCT (see also Rule 6.1(a) PCT) to such an extent that a meaningful search is impossible. Consequently, the search has been carried out for those parts of the application which do appear to be clear (and concise), namely claims 1 - 21

The present application only discloses a first rotation control mechanism for rotating the arm about a first axis wherein the first rotation control mechanism comprises a first rotational motor coupled to a first lead screw, and a bearing which moves longitudinally of the first lead screw as it rotates, the bearing being coupled to an offset crank of the arm.

The subject-matter defined in claims 22 and 23 is much broader and leaves unclear how the output of the first rotational motor is converted into a longitudinal motion and then back to rotational motion of the arm. The description does not support such subject-matter. Thus, no search has been carried out with respect to the subject-matter defined in claims 22 and 23.

The applicant's attention is drawn to the fact that claims, or parts of claims, relating to inventions in respect of which no international search report has been established need not be the subject of an international preliminary examination (Rule 66.1(e) PCT). The applicant is advised that the EPO policy when acting as an International Preliminary Examining Authority is normally not to carry out a preliminary examination on matter which has not been searched. This is the case irrespective of whether or not the claims are amended following receipt of the search report or during any Chapter II procedure.

INTERNATIONAL SEARCH REPORT

PCT/GB 03/03354

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
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